National Aeronautics Research and Development Plan

February
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About the National Science and Technology Council

The National Science and Technology Council (NSTC) was established by Executive Order 12881 on November 23, 1993. This Cabinet-level Council is the principal means within the executive branch to coordinate science and technology policy across the diverse entities that make up the federal research and development enterprise. Chaired by the President, the NSTC is made up of the Vice President, the Director of the Office of Science and Technology Policy, Cabinet Secretaries and Agency Heads with significant science and technology responsibilities, and other White House officials. For more information visit www.whitehouse.gov/ostp/nstc.

About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization and Priorities Act of 1976. OSTP's responsibilities include advising the President in policy formulation and budget development on all questions in which science and technology are important elements and articulating the President's science and technology policies and programs. For more information visit www.whitehouse.gov/ostp.

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

February 2, 2010

Dear Colleague:

To meet the aviation needs of our Nation now and in the future, the Federal government must continue to advance U.S. technological leadership in aeronautics by fostering a vibrant and dynamic aeronautics community that includes government, industry, and academia. A strong national program of research and development (R&D) for aeronautics technology forms the foundation of the U.S. aeronautics and aviation enterprise. Aeronautics R&D is critical for national security and homeland defense, an efficient national air transportation system, and the economic well-being and quality of life of our citizens.

This National Aeronautics Research and Development Plan (Plan) lays out high-priority national aeronautics R&D challenges, goals, and supporting objectives to guide the conduct of U.S. aeronautics R&D activities through 2020 as called for by Executive Order 13419 (National Aeronautics R&D), which established the National Aeronautics R&D Policy. As the first in a biennial update process, this Plan provides focused updates to a number of specific R&D goals and objectives in the National Plan for Aeronautics Research and Development and Related Infrastructure published in 2007.

Of particular note, this Plan includes an important new goal regarding the integration of unmanned aircraft systems into the National Airspace System. In addition, this R&D Plan:

- Supports the coordinated efforts of the Federal departments and agencies in the pursuit of stable and long-term foundational research;
- Ensures U.S. technological leadership in aeronautics for national security and homeland defense capabilities;
- Advances aeronautics research to improve aviation safety, air transportation, and reduce the environmental impacts of aviation;
- Promotes the advancement of fuel efficiency and energy independence in the aviation sector; and
- Spurs the development of innovative technologies that enable new products and services.

Through this Administration's continued emphasis on robust interagency planning to define and achieve high-priority national aeronautics R&D goals and objectives, we will help ensure that our Nation advances its technical leadership in aeronautics that is essential to our economic success and the protection of our security interests at home and around the globe.

Sincerely,

John P. Holdren

John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

BIENNIAL UPDATE

National Aeronautics Research and Development Plan

February 2010

Aeronautics Science and Technology Subcommittee

Committee on Technology

National Science and Technology Council

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OVERVIEW

On December 20, 2006, Executive Order (EO) 13419, "National Aeronautics Research and Development," established the nation's first policy to guide Federal aeronautics research and development (R&D) through 2020—the "National Aeronautics Research and Development Policy." EO 13419 stated, "Continued progress in aeronautics, the science of flight, is essential to America's economic success and the protection of America's security interests at home and around the globe." The EO also called for a national plan for aeronautics R&D and related research, development, test and evaluation (RDT&E) infrastructure to be developed and updated on a biennial basis.[1]

The National Aeronautics R&D Policy (Policy)[2] provided further guidance for a continuing series of aeronautics R&D plans and associated RDT&E infrastructure plans. The intent was to initially create separate R&D and RDT&E infrastructure plans concurrently, but it was realized that the RDT&E infrastructure plan would have to be phased to follow the R&D plan that would contain national research priorities and objectives, with associated time lines. Subsequently, the initial "National Plan for Aeronautics Research and Development and Related Infrastructure" was approved in December 2007.[3] This 2007 plan contained time-phased R&D goals and objectives, as well as the guidance for two follow-on products: (1) a technical appendix with additional technical material concerning the R&D goals and objectives, as well as a preliminary analysis of areas of concern where additional focus may be warranted, and (2) an RDT&E infrastructure plan aligned with the goals and objectives of the aeronautics R&D plan. The technical appendix was completed and published in December 2008.[4] In the future, the intent is to maintain two separate planning documents that will be updated biennially, the "National Aeronautics Research and Development Plan" (R&D Plan), which is solely focused on updating the R&D portions of the 2007 plan, and the "National Aeronautics RDT&E Infrastructure Plan." Between biennial updates to the R&D Plan, it is envisioned that an R&D progress report and an analysis of areas of concern will be completed to inform the subsequent R&D Plan. Hence, this "National Aeronautics Research and Development Plan" will be updated again in two years (commencing in 2011) following a progress report and analysis of areas of concern that is planned to be completed in 2010. The first National Aeronautics RDT&E Infrastruc-

1 Executive Order no. 13419, *Federal Register* 71, no. 247 (26 December 2006), http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-eo-2006.pdf.

2 Executive Office of the President, National Science and Technology Council, "National Aeronautics Research and Development Policy," December 2006, http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-natrdpolicy-2006.pdf.

3 Executive Office of the President, National Science and Technology Council, "National Plan for Aeronautics Research and Development and Related Infrastructure," December 2007, http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-natplan-2007.pdf.

4 Executive Office of the President, National Science and Technology Council, "Technical Appendix: National Plan for Aeronautics Research and Development and Related Infrastructure," December 2008, http://www.whitehouse.gov/sites/default/files/microsites/ostp/aero-techappen-2008.pdf.

ture Plan is anticipated by the end of 2010, and its initial update is anticipated to be completed in 2012 and biennially thereafter.

The National Aeronautics R&D Policy laid out seven key Principles to guide the conduct of the nation's aeronautics R&D activities through 2020. These Principles, with two exceptions noted below, continue to serve as the framework for this updated R&D Plan:

- Mobility through the air is vital to economic stability, growth, and security as a nation.
- Aviation is vital to national security and homeland defense.
- Aviation safety is paramount.
- Security of and within the aeronautics enterprise must be maintained.
- The United States should continue to possess, rely on, and develop its world-class aeronautics workforce.
- Assuring energy availability and efficiency is central to the growth of the aeronautics enterprise.
- The environment must be protected while sustaining growth in air transportation.[5]

For each Principle addressed in this R&D Plan, an updated description of the state of the art of related technologies and systems is provided. A set of fundamental challenges and associated high-priority R&D goals that seek to address these challenges follows. To give additional clarity and definition, the R&D Plan provides supporting objectives for each goal. These objectives are phased over three time periods: near term (<5 years), mid term (5–10 years), and far term (>10 years).

Note that two Principles in the Policy will continue to be addressed in different venues. Aviation security R&D efforts are coordinated through the "National Strategy for Aviation Security" and its supporting plans. Such R&D encompasses a wide array of areas, including personnel, baggage, and cargo screening; infrastructure protection; cyber security; and aircraft protection technologies. Aerospace workforce issues are being explored by the Interagency Aerospace Revitalization Task Force led by the Department of Labor pursuant to Public Law 109-420.

The challenges, goals, and objectives contained in this document were identified and subsequently updated through the consensus of the departments and agencies on the Aeronautics Science and Technology Subcommittee of the National Science and Technology Council, with input from the broader community and non-Federal stakeholders, in concert with studies on aeronautics such as the National Research Council's *Decadal Survey of*

5 Energy and Environment were separate Principles in the Policy; however, they are sufficiently integrated that they are considered together in this Plan.

Civil Aeronautics.[6] The members of the Aeronautics Science and Technology Subcommittee involved in the updating of this Plan included representatives from the Departments of Commerce, Defense, Energy, Homeland Security, State, and Transportation, as well as from several Federal agencies and offices, including the Environmental Protection Agency (EPA), the Federal Aviation Administration (FAA), the Joint Planning and Development Office, the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the National Science Foundation.

The goals and objectives for each Principle in this Plan are considered the highest priority and are intended to provide high-level guidance for foundational, advanced aircraft systems, and air transportation management systems R&D through 2020. While the challenges, goals, and objectives are organized by the Principles outlined above, most of the R&D goals and objectives will require stable and long-term foundational research across a breadth of aeronautics disciplines to provide the underlying basis for new technological advances and breakthroughs. Such foundational research is often cross-cutting, resulting in technology advances that have applications across several Principles. Moreover, new ideas and technologies that are generated by foundational research will help inform future updates to this Plan.

These goals and objectives are not intended to endorse specific technologies or assign priorities to research areas within those Principles. It is important to quantify the progress toward achieving these goals and objectives to the greatest possible extent. Hence, where possible, appropriate metrics have been developed and baseline values have been defined. As part of the biennial review process, these metrics and baseline values were reevaluated and re-baselined as needed. It must be stressed that in addition to these goals and objectives, departments and agencies have mission-specific and unique R&D activities that may not have been prioritized for this interagency national Plan; however, their exclusion does not diminish their importance or the need to pursue them.

Several revisions have been incorporated in this biennial update to the R&D Plan, including expanded coverage of unmanned aircraft systems (UAS) in the mobility, national security and homeland defense, and safety sections. The additions describe the high-level expectations and R&D necessary to eventually achieve UAS integration into the National Airspace System (NAS). Other additions besides those related to UAS include an expanded focus on the verification and validation of complex systems and updated material for aviation bio-fuels and emissions reductions.

6 http://www.nap.edu/catalog.php?record_id=11664#toc.

ORGANIZATIONAL PROGRESS

The National Aeronautics R&D Policy and the R&D Plan provide a strategic framework to help shape, focus, and coordinate high-level aeronautics R&D efforts. Since its initial publication two years ago, the R&D Plan has become incorporated within the planning processes of the Federal departments and agencies, which in turn has helped to coordinate and guide national aeronautics research and development. Additionally, awareness is growing within the broad non-federal aeronautics R&D community as a result of public outreach and the networking that occurs from having a published national R&D Plan available for discussion, critique, and continuing input—provided as a part of the R&D Plan update processes.

INTRA–AGENCY RESEARCH

The R&D Plan has helped to create consistency among Federal research programs focused on addressing the R&D Plan goals and objectives. Moreover, Federal departments and agencies conducting aeronautics R&D have begun to incorporate the R&D Plan into their high-level aeronautics R&D processes. The examples below demonstrate the ways in which individual departments and agencies have capitalized on their particular expertise and resources to build and accelerate progress toward R&D Plan objectives:

- Peer reviews of NASA program and project activities use the R&D Plan as a benchmark when assessing relevance, performance, and quality.
- The R&D Portfolio Development Process Guidance Reference Document that governs FAA research portfolio development uses the R&D Plan as a source of strategic guidance. FAA's 2009 National Aviation Research Plan refers explicitly to the Policy and to the R&D Plan.
- At the Department of Defense (DOD), the new Air Platforms Community of Interest assumes responsibility through its charter for the DOD's implementation of the national security and homeland defense section of the R&D Plan. The Air Platforms group is integrating the formulation and review of fundamental challenges, goals, and objectives from the R&D Plan as part of its internal coordination, planning, and reporting activities.

INTERAGENCY AND COLLABORATIVE RESEARCH

The focus on crosscutting objectives in the R&D Plan has strengthened interagency collaboration organized around the Plan goals and objectives, and it has led to improved interagency coordination and communication:

- NASA and the Air Force have established an Executive Research Council that meets at least twice a year to ensure close coordination of research.

- The DOD has initiated a strategic planning activity for future vertical lift aircraft and rotorcraft and is working with NASA to leverage NASA expertise and develop a national view.
- The DOD is working in coordination with NASA to develop an integrated hypersonics research agenda.
- The FAA created the Continuous Low Emissions, Energy and Noise (CLEEN) program and NASA created the Environmentally Responsible Aviation (ERA) project. These programs are guiding coordinated efforts to bring to maturity new technologies to reduce fuel burn, emissions, and noise.
- The FAA, NASA, EPA, and DOD are all participants of the Commercial Aviation Alternative Fuels Initiative (CAAFI). The FAA, NASA, and the EPA are jointly populating emissions prediction models with empirical data from emerging renewable aviation fuels. In addition, the Air Force and the FAA have led efforts to develop frameworks for the calculation of life-cycle greenhouse gas emissions from alternative aviation fuels.
- The FAA, with support from other organizations such as EPA, NOAA, and NASA, are collaborating through the Aviation Climate Change Research Initiative (ACCRI) to identify and address key scientific gaps and uncertainties with respect to non-carbon dioxide (CO_2) aviation climate impacts that were discussed in the Technical Appendix of the National Plan for Aeronautics R&D and Related Infrastructure.

MOBILITY THROUGH THE AIR IS VITAL TO ECONOMIC STABILITY, GROWTH, AND SECURITY AS A NATION

Providing for mobility requires an aeronautics enterprise with sufficient capacity to meet increasing demand for air travel and transport and with sufficient flexibility and affordability to accommodate the full range of aircraft requirements and attributes. Possessing the capability to move goods and people, point-to-point, anywhere in the nation and around the world is essential to advance the local, state, and national economies of the United States. Furthermore, the United States, in cooperation with international partners, should play a leading role in ensuring global interoperability.

INTRODUCTION

Mobility through the air is a key function of the nation's air transportation system. The U.S. economic system revolves around the capability to move goods and people efficiently throughout the nation and the world. Aviation contributes an estimated $741 billion to the U.S. economy or roughly 5.6 percent of the nation's gross domestic product. Over 11 million jobs with $369 billion in wages are estimated to be associated with the aviation industry. The aerospace products and parts sector is the largest U.S. manufacturing exporter and contributes a net surplus of approximately $61 billion to the U.S. trade balance.[7] Enabling mobility through the air with sufficient flexibility and affordability to accommodate the full range of aircraft requirements and attributes, as well as projected passenger and cargo traffic, is essential to America's economic success.

As a result of the recent worldwide economic turmoil and the volatility of fuel prices, projections for air traffic in the 2025 time period have varied considerably. The FAA's forecast of the growth of passenger enplanements and operations between 2008 and 2025 was reduced between 35–40% in its Terminal Area Forecast (TAF) Summary 2008–2025 as compared to the TAF for the 2007–2025 time period. However it is interesting to note that the active general aviation fleet is forecast to grow almost 20% during the next 17 years with the more expensive, and sophisticated turbine-powered fleet (including rotorcraft) and turbine jet fleet expected to grow at forecast rates of 3.2% and 4.8%, respectively, between 2008 to 2025 (FAA Forecast 2009). Additionally, increased operations involving very light jets, UAS, rotorcraft, and suborbital space vehicles are possible. These projections have led to increased uncertainty in demands on the NAS by 2025. Additionally, by 2025, the possibility exists that new aircraft with significant changes in their performance capabilities will join the fleet (e.g., hybrid-wing body aircraft, supersonic business jets and small transports, and advanced rotorcraft). The message remains clear that by 2025, the NAS needs to be scalable and flexible to accommodate a significant increase in the number of operations,[8] as well as significant changes in the capabilities of the fleet. The environment where the NAS

7 Federal Aviation Administration, "The Economic Impact of Civil Aviation on the U.S. Economy," October 2008, http://www.faa.gov/about/office_org/headquarters_offices/ato/media/2008_Economic_Impact_Report_web.pdf

8 Operations are defined as takeoffs and landings.

must accommodate a projected increase in the number of operations over a 2004 baseline[9] is referred to as the "A× environment" where A refers to the growth factor over 2004 (e.g., 1.8× refers to an environment to accommodate 1.8 times the number of operations that occurred in 2004). Finally, the future NAS must help enable the capabilities necessary to provide for aviation security, national security and homeland defense, and the required reduction in environmental impacts from aviation.

There are clear signs that the nation's air traffic management system is under serious stress as a result of current demand levels. The system is extremely sensitive to local perturbations and reacts with system-wide ripple effects. Delays result in a huge cost to industry, passengers, shippers, and government. The forecast growth in air transportation over the next two decades has also triggered community concerns over aircraft noise, air quality, and congestion. Many market-based, economic solutions could be pursued to reduce congestion, such as implementing congestion pricing or developing an alternative to first-come-first-served service. These have not been fully explored yet. Despite these potential nearer term solutions, current demand predictions still point to the need for a fundamental transformation of the NAS for long-term growth, which is the focus of the R&D recommendations in this section.

A mandate for the design and deployment of a transformed air transportation system was established in *Vision 100 – Century of Aviation Reauthorization Act* (Public Law 108-176).[10] The law established a Joint Planning and Development Office (JPDO) representing six government departments and agencies and the private sector to develop the Next Generation Air Transportation System (NextGen – formerly referred to as NGATS). NextGen will entail a revolutionary transformation of the U.S. airspace system to a performance-based, scalable, network-enabled system that will be flexible to adapt to meet future needs. Achieving NextGen will require focused and coordinated R&D to address key decisions and challenges associated with system transformation.

In the sections on mobility and energy and environment, this document will refer to future generations of advanced aircraft with enhanced capabilities using the following notation:

- "N" refers to the current generation of tube-and-wing aircraft.
- "N+1" represents the next generation of tube-and-wing aircraft.
- "N+2" refers to advanced aircraft in the generation after N+1, which are likely to use revolutionary configurations (such as hybrid wing-body, small supersonic jets, cruise-efficient short takeoff and landing and advanced rotorcraft).
- "N+3" refers to the generation of aircraft after N+2, which have dramatically improved performance and reduced noise and emissions.

9 The year 2004 was chosen as a baseline for consistency with the *Vision 100 – Century of Aviation Reauthorization Act* (P.L. 108-176) and the Next Generation Air Transportation System Integrated Plan submitted to Congress as required in that legislation.

10 http://www.jpdo.gov/vision_100_law.asp.

STATE OF THE ART

Today's aircraft operate with inefficient procedures that are very similar to those created over 30 years ago. The NAS is a large, complex, distributed, and loosely integrated network of systems, procedures, and infrastructure, much of it decades old. Air traffic control is performed primarily through the use of surveillance radars, voice radio systems, limited computer support systems, and numerous complex procedures. The NAS's operating procedures were originally designed around technologies now considered antiquated, yet these procedures remain largely unchanged despite new concepts of operation afforded by current and near-term technologies.

The resulting inefficiencies pose severe cost and capacity limitations on aviation growth. Uncertainties in the total flight environment negatively affect system throughput. Uncertainty is managed by queuing traffic to be serviced, and demand is managed by restricting access to the airspace to avoid straining capacity. On the airport surface, runway incursions and missed taxi clearances result from a lack of situational awareness and communication limitations for operators or traffic controllers.

The use of unmanned aircraft in the NAS remains limited despite the growing demand in both the military and civil aviation sectors. Existing Federal regulations and procedures do not allow routine UAS access to the NAS. Furthermore, existing access methods are not sufficiently scalable to address current mission needs or commercial demand. Addressing the demand is tightly coupled with integration of UAS into civil airspace. Achieving safe UAS integration depends on a complex set of regulatory, technical, economic, and political factors that must be addressed in an integrated and systematic fashion. Furthermore, it is becoming increasingly clear that meeting the future expectations of the departments, agencies, and commercial users will require that the end-state operational vision provide for full integration of manned and unmanned systems throughout the NAS.

FUNDAMENTAL MOBILITY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art will have to be overcome to achieve mobility during the decades ahead. The following are major challenges:

- Reducing separation distances between aircraft to increase traffic density and determining functions that can be moved to the cockpit to improve operations without compromising safety.
- Developing the capability to perform four-dimensional (space plus time) trajectory based planning as a foundational component of NextGen.
- Dynamically balancing airspace capacity to meet demand by allocating airspace resources and reducing adverse impacts associated with weather.
- Developing more accurate and timely observations and forecasts of aviation-relevant weather to enable a key part of NextGen.
- Increasing airport approach, surface, and departure capacity.

- Developing airport terminal designs that facilitate passenger throughput, including movement between surface and air transportation modes.
- Introducing new generations of air vehicles, including rotorcraft, with vastly improved performance and revolutionary capabilities such as shorter takeoff and landing, faster (supersonic) speeds, and larger passenger and cargo capacity, while also achieving significantly reduced environmental impact.
- Integrating new aircraft capabilities for all classes of aircraft, including UAS, and enhanced NAS operations to enable improved methods of operating aircraft within the NAS and to ensure that mobility will not be curtailed because of environmental constraints.
- Defining appropriate roles for humans (notably air traffic controllers and pilots) in relation to automation, and developing automation that humans can reliably and fluidly interact with, monitor, and, when appropriate, override.
- Understanding enterprise-level issues (e.g., environmental, organizational) and interactions critical to successful transformation.

MOBILITY R&D GOALS AND OBJECTIVES

The future vision for air transportation calls for a system-wide transformation leading to an enhanced set of system capabilities. These include communication and physical infrastructure, the acceleration of automation and procedural changes based on four-dimensional (space and time) trajectory analyses, dynamic reconfiguration and reallocation of the airspace to be scalable to geographic and temporal demand, and an aircraft fleet designed to leverage these enhancements. Addressing the major challenges to this system-wide transformation requires achieving the five key goals and associated time-phased objectives listed below. However, this does not imply that focused research associated with the mobility goals and objectives alone is sufficient. Foundational research provides the "building blocks" of a technology base to successfully address the stated goals and objectives. Hence, complementary foundational aeronautical research efforts are also required in areas such as guidance, navigation, and control; fluid mechanics; advanced structures and materials; combustion chemistry; airframe/propulsion system integration; and advanced mathematics, statistics, computational science, and optimization techniques.

Another major challenge is to define the proper balance in responsibility between humans and automation. Research into the human-machine relationship does not appear as a set of separate research topics in the mobility goals and objectives table because it must be an integral part of research to define the details of new operational capabilities identified in Goals 1–4. Human-machine integration efforts are also identified in the national security and safety sections. Verification and validation of a complex system like NextGen, during all phases of the research, development, and implementation cycles, is critical to the success of the mobility improvements identified in this plan. R&D to address this issue is identified in the safety section of this report. Both the human-machine integration and the

verification and validation efforts will have to place added emphasis on the concept of performance under off-nominal conditions.

The need for focused foundational technology research is clear, but the importance of addressing the larger air transportation enterprise level issues and their role in transforming the air space system has become equally apparent. Near- and long-term multidisciplinary research is needed to help inform the policy decisions related to the economic, environmental, institutional, organizational, multimodal coordination and transition challenges associated with deployment of the future air transportation system. An area of particular importance is research to find ways to expedite the process for environmental approvals, for certification of new systems, and approval of new procedures.

Note, for the purposes of the mobility goals and objectives, "enable" means to advance the development of technologies or systems to levels that appropriately facilitate eventual industry uptake for commercial applications; implementation will add to the time line.

Goal 1—Develop reduced aircraft separation in trajectory- and performance-based operations (see p. 21)

Reduced aircraft separation will require a move to trajectory-based operations, performance-based navigation, and a paradigm shift in control with new allocation of responsibilities between air and ground and between humans and automation. At the core of the paradigm shift is focused research on aircraft trajectories. Research into trajectory prediction, synthesis, and uncertainty is an enabler for separation assurance, dynamic airspace configuration, traffic flow management, and reduced environmental impact for both current operations and future super density operations across all flight domains.

Performance-based navigation provides a basis for the design of automated flight paths, airspace design, aircraft separation, and obstacle clearance and defines how an aircraft will execute a trajectory. Research into candidate concepts of operations and enabling technologies is needed for any change in separation responsibility from ground controllers to the cockpit. Research on methodologies to translate weather information into operational information to be integrated into decision support tools for use by humans and air traffic management system automation is also required. Technologies supporting positioning, navigation, and timing capabilities are key enablers for separation management. Developing enhanced positioning, navigation, and timing capabilities, including identifying feasible backups, is a critical research focus. This research must investigate a means to take advantage of existing and future avionics capabilities to expand (1) the rapidly growing set of applications, such as Automatic Dependent Surveillance-Broadcast, and (2) area navigation and required navigation performance in the terminal and en-route environments. The research must also investigate impacts to pilot and controller (and other vital personnel, such as airline operators and remote aircraft operators) workload, and roles and responsi-

bilities for automated route clearances. Another major research challenge is to define the proper balance in responsibility between the ground and the cockpit. Finally, this research must support the definition of new separation standards, procedures for trajectory-based operations, and certification of new ground- and cockpit-based systems, including the development of methods for analyzing the safety of any proposed new separation procedures.

Goal 2—Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies (see p. 21)

As demand grows, enhanced traffic management techniques based on four-dimensional aircraft trajectory updates that take weather information and other airspace resources and constraints as well as environmental considerations into account will be required in order to balance NAS capacity to future demand. A basic underlying tenet will seek to maximize operators' opportunities to use the system rather than to constrain flight demand. Enhanced flight plan negotiations and improved situational awareness are necessary to accommodate operators' preferences and impose restrictions only where necessary. System capacity increases are sought by dynamically restructuring the airspace, by dynamically allocating system resources (including people), and by promptly communicating system status to all users. Research is required to identify flexible airspace structures, including boundaries, trajectory predictions, routes, or performance requirements, that can be dynamically adjusted to meet demand. In addition, research must determine the proper use of weather information by humans and automation and ensure effective integration of weather information into decision support tools. These integrated air transportation decision support tools will require accurate and reliable observations and probabilistic weather forecasts shared in a common weather picture to provide optimal NAS performance (see Goal 3).

The needs of both military and civilian operators will be balanced through enhanced solutions for effective airspace utilization. This requires research focused on advanced concepts for collaborative air traffic management with attention paid to appropriate roles for humans and automation. Dynamic adjustments of airspace configurations to meet demand must interact with a traffic flow management function, and this interaction will be on multiple temporal scales: annual, seasonal, monthly, weekly, daily, and hourly. Because the future traffic demand is expected to have a diverse fleet mix and a broader mix of operators, new traffic flow management concepts must be developed. The complex interaction between the separation management function and the traffic flow management function must be researched to understand the level of allowable traffic complexity in the design of traffic flows. In addition, high-density traffic flows especially need to be robust during off-nominal conditions, such as when an aircraft deviates from its assigned trajectory. This may require a balance between eliminating all predictable sources of variation in traffic spacing versus maintaining sufficient separation in the traffic flows to adjust for unexpected circumstances. Research supporting the development of traffic flow models to systematically assess advanced concepts is also required to advance this goal.

Goal 3—Reduce the adverse impacts of weather on air traffic management decisions (see p. 21)

A key component of air traffic management research will be to understand the operational impact of uncertainties due to weather. A common weather picture (shared situational awareness) of forecasts and observations from which all weather-related decisions are made by multiple decision-makers is needed. Research must help determine the spatial and temporal resolution and accuracy of weather information required for decision support capabilities in air traffic management automation systems. Focused research is necessary to develop real-time verification systems that quantitatively assess the accuracy and reliability of probabilistic weather forecasts. This includes generation of the following aviation weather parameters: convection, winter storms, icing, turbulence, winds, volcanic ash, ceiling, and visibility. A key concept to facilitate this goal is the NextGen Network Enabled Weather virtual database capability. With NextGen Network Enabled Weather capabilities, observations and forecasts will be arbitrated and merged into a single authoritative source of weather information to be translated into operational information for use in joint government/user NextGen decision-making processes. This research is an important precursor to enhanced situational awareness (in particular enhanced flight deck displays of weather conditions and forecasts) discussed in Goal 2 in the aviation safety section. Focused research is also required to understand the disparate translations of this single authoritative source of weather information by all stakeholders and their impact on decision-making processes.

Goal 4—Maximize arrivals and departures at airports and in metroplex areas (see p. 21)

Throughput in high-density, complex terminal airspace is currently limited by several factors. Procedures designed around now-antiquated technology lead to inefficient use of terminal area airspace. The efficacy of technologies to reduce separations and improve flight paths for high-density arrival and departure traffic flows, which may include aircraft with quite different performance characteristics, will be highly dependent on automation and precision positioning, navigation, and timing. R&D activities focused on a more thorough understanding of wake turbulence transport and decay can potentially allow for decreased separation standards and subsequent increased throughput for single and multiple runways. To accommodate increased arrival and departure rates, especially during low-visibility conditions, improvements in surface operations, situational awareness, and integration of weather information into decision support tools will be needed.

Research will lead to time-based metering of flows from metroplex areas (two or more adjacent airports where the arrival and departure operations are highly interdependent) into en-route traffic streams and to the integration of performance-based trajectory management tools and techniques for both arrival and departure flow in transitional airspace (defined as the portion of controlled airspace where aircraft change from one phase of

flight or flight condition to another, for example, to/from the en-route to terminal environment). Since some noise abatement procedures constrain operations in this transitional airspace, technologies to enable approach and departure paths (including straight-in arrivals and straight-out departures) should be explored to enable improved noise and emission footprints. This research will allow for significant airspace design flexibility to exploit new roles for humans and automation and for performance-based trajectories while taking into account constraints such as those due to different aircraft performance characteristics and to environmental restrictions.

Goal 5—Develop expanded manned and unmanned aircraft system capabilities to take advantage of increased air transportation system performance (see p. 22)

Realizing the maximum performance of the NAS requires an aircraft fleet designed in conjunction with the NAS itself. This goal focuses on developing knowledge, data, capabilities, technologies, and design tools for the classes of vehicles envisioned to be part of the commercial and general aviation fleets. These vehicles may have widely varying performance characteristics (e.g., rotorcraft or supersonic vehicles), with operational paradigms ranging from conventionally piloted vehicles to autonomous operations.

UAS pose significant challenges as they represent a diverse set of aircraft, control stations, autonomous systems, and communications methods. Unmanned aircraft span a wide spectrum of size, endurance, and performance characteristics, often different from manned aircraft (e.g., slower cruise speeds and climb rates). NextGen capabilities such as net-centric operations, four-dimensional trajectory management, flexible separation management, dynamic airspace configuration, and collaborative flow contingency management all present opportunities for UAS mobility, access, and integration into civil airspace. UAS R&D is intended to cover a broad range of activities and the reader is also directed to the national defense and homeland security and aviation safety sections for additional UAS content. In particular, note that Goal 6 under the National Security and Homeland Defense R&D Goals and Objectives focuses on the integration of UAS into the NAS. Specific objectives across the near-, mid-, and far-term address the demonstration of sense-and-avoid capability for UAS operating in airspace environments ranging from low-density operations to high-density, metroplex terminal operations.

The present goal is complementary to military aircraft and the goals described in both the national security and homeland defense and aviation safety sections. Further, this goal is based on the premise that to make revolutionary aircraft improvements possible, understanding the complete system (the aircraft and the air transportation system they fly in) is required. For this purpose, R&D is needed to credibly predict future improvements in NAS capacity that can be obtained while maintaining or improving safety standards and adhering to more restrictive environmental regulations.

Key advances in aircraft technologies, based on long-term, stable foundational research, are needed to bring about significant changes in the current fleet mix, such as advances in materials, physics-based flow prediction and control technologies, configurations, subsystems (including projected advances in machine intelligence), and components. For example, the fuel burn of future air vehicles (including supersonic air vehicles) must be decreased significantly, along with their noise and emissions (see Goals 2 and 3 included in the energy and environment section).

Additional access capabilities will be provided by future aircraft that are able to take off and land with significantly reduced field lengths. Economically viable aircraft capable of supersonic speeds over land with an acceptable sonic boom impact (see Goal 3 of the energy and environment section) are also envisioned. Future rotorcraft concepts may also be developed to obtain a combination of vertical or short takeoff and landing capabilities and efficient cruise. Methods and systems are expected to be developed that will allow UAS operations in the NAS with no negative impact on other operations (e.g., improved sense and avoid capability will help ensure safe UAS operations). Because of the highly integrated nature of the technologies that will be required to bring about these revolutionary improvements, the development of high-fidelity, physics-based, multidisciplinary analysis and design capabilities is included in this goal, as is ensuring that validation and verification plans for these new capabilities are put in place.

Finally, this goal addresses the need to introduce new component technologies and vehicle concepts into the system in a timely fashion. Research in advanced manufacturing capabilities and changes in certification processes can decrease the cost and time for the introduction of new aircraft and aircraft subsystems without compromising safety. Research results are a critical source of information that informs the certification process. Timely, verified results from research studies are of particular importance in the development and allocation of requirements, standards, and criteria for certification of aircraft capabilities and operating procedures. Although final approval is the responsibility of the certification services, standards development requires the involvement of, and input from, the full stakeholder community, including government and non-government entities.

Table 1. Mobility R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Develop reduced aircraft separation in trajectory- and performance-based operations (see p. 16)	Develop separation standards that vary according to aircraft performance and crew training Develop nonradar 30-mile separation procedures for pair-wise maneuvers in oceanic airspace	Develop 5-mile nonradar separation procedures for current nonradar airspace Develop positioning, navigation and timing precision requirements for fixed- and variable-separation procedures	Demonstrate self-separation in at least one airspace domain Validate performance-based variable separation standards for multiple domains
	Develop Automatic Dependent Surveillance-Broadcast 3- to 5-mile spacing Develop positioning, navigation and timing (including backup) capabilities to support NextGen	Develop merging and spacing tools for continuous descent approaches that balance capacity and environmental considerations Establish the basis for separation standards to increase airspace density	Implement human-machine and air-ground interaction methods in a highly automated air transportation system
Goal 2 Develop increased NAS capacity by managing NAS resources and air traffic flow contingencies (see p. 17)	Develop advanced airspace design concepts to support scalability to 3× operations Develop Special Use Airspace and general aviation access procedures to maximize capacity to match demand	Develop dynamically adjustable advanced airspace structures—including flow corridors—scalable to accommodate an interim target of an environment supporting 2× operations Develop methodologies for the dynamic allocation of NAS resources	Demonstrate dynamic allocation of NAS resources Develop automated flight and flow evaluation and resolution capabilities to support Air Navigation Service Provider negotiations
	Develop trajectory management methods for collaborative preflight routing including prediction, synthesis, and negotiation Develop comprehensive strategies to translate weather information into operational impacts and integrate those impacts into decision support tools	Integrate weather information into flow management decision support tools	Demonstrate gate-to-gate trajectory-based flight planning and flow management to increase NAS efficiency, capacity, and reduce weather delays and environmental impact
Goal 3 Reduce the adverse impacts of weather on air traffic management decisions (see p. 18)	Develop resolution and accuracy requirements for weather observation and forecasting information Develop requirements for probabilistic weather prediction systems and methods for communicating forecast uncertainty	Develop technologies for sharing weather hazard information measured by on-board sensors with nearby aircraft and ground systems and vice-versa Develop probabilistic weather forecast products that communicate uncertainty information	Integrate weather observation and forecast information in real time into a single authoritative source of current weather information Develop air traffic management decision strategies to reference a single authoritative weather source, including understanding impacts of disparate interpretations of the data
	Develop initial capability for net-centric four-dimensional weather information system, including enabling fusion of multiple weather forecast and ground and airborne observation products and researching the roles of humans in applying operational expertise to augment automated, four-dimensional weather grids	Develop severity indices for aviation weather hazards using observations and forecasted weather data for short-to-long range decision making Develop capabilities to translate weather severity information into adverse weather information for operational use	Demonstrate NextGen Network-Enabled Weather capabilities to reduce adverse impacts
Goal 4 Maximize arrivals and departures at airports and in metroplex areas (see p. 18)	Develop traffic spacing/management technologies to support high-throughput arrival and departure operations while minimizing environmental impact	Develop technologies and procedures for operations of closely spaced parallel runways Integrate weather information into terminal area decision support tools	For a system that is scalable to 3× operations: Reduce lateral and longitudinal separations for arrival and departure operations Demonstrate technologies and procedures to support surface operations Develop time-based metering for flows transitioning into and out of high-density terminals and metroplex areas to enable significant airspace design flexibility and reduced environmental impact
	Develop time-based metering of flows into high density metroplex areas	Develop performance-based trajectory management procedures for transitional airspace	
	Develop technology to display aircraft and ground vehicles in the cockpit to guide surface movement	Develop operations and procedures to integrate surface and terminal operations, especially in low-visibility conditions	

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 5 Develop expanded manned and unmanned aircraft system capabilities to take advantage of increased air transportation system performance (see p. 19)	Develop validated multidisciplinary analysis and design capabilities with known uncertainty bounds for N+1 aircraft, and develop procedures for the interaction of a variety of vehicle classes with the airspace system (including N+1, very light jets, UAS, and other vehicle classes that may appear in the system)	Develop validated system analysis and design capabilities with known uncertainty bounds for N+2 and N+3 advanced aircraft, including their interaction with the airspace system	Develop suitable metrics to understand realizable trades between noise, emissions, and performance within the design space for N+2 and N+3 advanced aircraft
	Develop dynamic, need-based "fast-track" Federal approval process for airframe and avionics changes Develop aircraft capability priorities for NextGen through 2015 to support standards development and certification	Develop N+2 aircraft fleet and associated capabilities to support the development of procedures, policies, and methodologies for reduced cycle times to introduce aircraft and aircraft subsystem innovations	Continue development and refinement of procedures, policies, and methodologies supporting reduced cycle times for introduction of advanced (N+3 and beyond) aircraft and associated subsystem innovations
	Enable commercial supersonic aircraft cruise efficiency 15% greater than that of the final NASA High Speed Research (HSR) program baseline	Enable advanced technologies for N+2 aircraft with significantly improved performance and environmental impact Enable commercial supersonic aircraft cruise efficiency 25% greater than that of the final NASA HSR program baseline Enable the development of N+2 cruise-efficient short takeoff and landing aircraft, including advanced rotorcraft, with between 33% and 50% field length reduction compared with a B737 with CFM56 engines*	Enable advanced technologies for N+2 and N+3 aircraft with significantly improved performance and environmental impact Enable N+2 and N+3 commercial supersonic aircraft cruise efficiency 35% greater than that of the final NASA HSR program baseline (through reductions in structural and propulsion system weight, improved fuel efficiency, and improved aerodynamics and airframe/propulsion integration)

* The reference aircraft is a B737-800 with CFM56/7B engines, representative of 1998 entry into service technology.

AVIATION IS VITAL TO NATIONAL SECURITY AND HOMELAND DEFENSE

Aviation is a central part of America's National Security Strategy, providing needed capabilities to project military power around the globe in defense of U.S. interests and overcome a wide range of national security challenges. At the same time, the military must possess the ability, at a moment's notice, to seamlessly use the national airspace system for defense anywhere within and approaching U.S. borders.

INTRODUCTION

The United States faces a changing national security environment in which the Federal Government must address a broad range of challenges such as nontraditional, irregular warfare with non-state actors, weapons of mass destruction that could be used by either state or non-state actors, and disruptive technological advances by other states that could change the nature of warfare. The United States must also advance its technological advantage to retain air superiority in traditional peer-on-peer conflict. Growing aircraft acquisition costs and a need for shorter development cycles require that aeronautics R&D take a more strategic planning approach to mature new technologies and capabilities, while sustaining a robust technology base to support and advance U.S. military capabilities far into the future.

STATE OF THE ART

Aviation provides for many of the strategic and tactical needs of the warfighter, including strike; air superiority; command, control, intelligence, surveillance, and reconnaissance; and airlift. The military Services operate a variety of fixed- and rotary-wing aircraft in support of military operations. The Services continue to upgrade existing aircraft systems and acquire new systems with greater capability, though the rate of replacement is such that current air fleets are aging and many systems will be flying well beyond their original design lifetimes. The United States must continue to advance aviation technologies that provide increased capabilities to maintain its military effectiveness over potential adversaries. Moreover, today's uncertain security environment requires new approaches that increase battlespace awareness and flexibility to address a range of national security challenges. Aviation also provides a key component to disaster recovery and law enforcement activity, as well as humanitarian operations. Technology must address growing military acquisition and operating costs through advanced design and manufacturing capabilities, greater platform efficiency, and reduced maintenance costs and increased availability, while continuing to advance domestic capabilities for homeland defense operations.

FUNDAMENTAL TECHNICAL CHALLENGES TO OVERCOME

A number of fundamental challenges are barriers to technical progress, as well as opportunities for advancement through sustained aeronautics R&D:

- Improved aerodynamics and innovative airframe structural concepts for high-efficiency fixed- and rotary-wing aircraft would provide greater aircraft range, endurance, survivability, and payload capability.
- Quiet, efficient rotorcraft would be more operationally effective, more survivable, and less expensive to operate.
- Highly efficient propulsion systems would enable greater range and endurance and could provide greater mission flexibility.
- Integrated power and thermal management on aircraft is becoming increasingly important as power requirements and heat loads increase.
- High-speed and hypersonic flight offers advantages for national security in terms of global reach, responsiveness, and survivability.
- Finally, airspace integration and deconfliction, especially as UAS become ubiquitous to aviation operations, are growing issues affecting not only military operations, but civil operations as well.

NATIONAL SECURITY AND HOMELAND DEFENSE R&D GOALS AND OBJECTIVES

National security and homeland defense aeronautics R&D plans are organized around capability-based planning concepts. Because certain capabilities share a common technology base, the goals identified in this section address the relationship between technological advancements and multiple capability areas. These goals represent a significant advance in the state of the art in terms of technology and current aviation capabilities, and they will continue to evolve as technology advances and in response to national security needs. In general, the Department of Defense seeks to develop technologies to a level where they can be validated or demonstrated in a relevant environment and ultimately be employed in weapon systems. This validation or demonstration may include flight test, ground test, validated modeling and simulation, and any other means as appropriate to enable the transition of technologies into the development of aviation systems for national security and homeland defense. However, there are areas of research where this guidance does not necessarily apply, such as with concept development or knowledge generation that is necessary to support a robust technology base. In addition to the objectives defined here, ongoing foundational aeronautics research efforts in areas such as propulsion; aerodynamics; materials and structures; guidance, navigation, and control; acoustics; and mathematics and computational science focus on sustaining a robust technology base to continue to support and advance the nation's defense capabilities.

It should be noted that there is a relationship between several of the goals here and the goals in the energy and environment section of this Plan. The first four goals here focus on energy efficiency, power, and thermal management. From a national security perspective, the focus of these research activities is the mission capability gained from more effective

use of energy. However, there are significant opportunities as expressed by these goals to reduce energy consumption in national security endeavors, as well as associated improvements in environmental impacts.

Goal 1—Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft (see p. 28)

The ability to cruise efficiently at a range of altitudes, enabled by a substantial increase in cruise lift-to-drag ratios over today's high-altitude reconnaissance aircraft, is a critical goal and key element in support of national security, providing sustained presence, long range, and advanced sensing capabilities. Specific technologies include innovative configurations; large, lightweight, adaptive, and actively controlled wing and fuselage structures; lightweight, high strength, stiff materials; structurally integrated sensors; physics-based transition prediction; novel flow control techniques; and advanced flight controls. Several of these technologies, as well as other structural concepts and aerodynamic configurations and technologies, are also applicable to mobility aircraft, that is, aircraft that provide airlift for national security and homeland defense materiel and personnel. For these applications, improvements in lift-to-drag ratios on the order of 25% compared with modern tube-and-wing aircraft would provide a significant advance in national security capabilities. Research efforts for mobility aircraft also leverage some of the work described in the energy and environment section for reducing aircraft fuel burn.

Goal 2—Develop improved lift, range, and mission capability for rotorcraft (see p. 28)

Future national security plans will benefit from rotorcraft systems that have (1) significantly improved lift, range, survivability, and mission capability compared with year 2005 state-of-the-art technology and (2) an overall reduction in logistics and cost of operation. The critical technologies to support these capabilities include the following:

- Advanced rotors and rotor hubs, possibly with active blade control, that produce higher lift with reduced loads, vibration, noise, and downwash over a range of flight conditions.
- High-speed, high-torque drive trains that are quieter, more robust, and require less maintenance.
- Rotors, prop-rotors, transmissions, propulsion systems, and vehicle control systems that allow large variations in rotor speed and a wider range of operation.
- Advanced digital flight control systems, vehicle management systems and system architectures that enable enhanced aircraft safety and survivability, improve handling qualities, reduce platform weight, reduce life cycle cost, and support a diverse range of vehicles and missions.

It should be noted that the current goal and objectives presented in the National Defense and Homeland Security Table are based on improvements that could be achieved through modifications or upgrades to current aircraft. The DOD, working with other Federal departments and agencies, is evaluating future capabilities for rotorcraft through strategic planning efforts that will inform and may impact the goals and objectives at the next biennial update.

Goal 3—Demonstrate reduced gas turbine specific fuel consumption (see p. 28)

A primary long-term goal in aircraft propulsion is to reduce system specific fuel consumption by more than 30% over gas turbine engines using year 2000 state-of-the-art technology. Such an advance in propulsion system performance would provide important improvements in aircraft range, endurance, mission flexibility, and payload capability. Technical challenges being pursued include efficient, high overall pressure ratio compression systems; variable cycle engine technologies; advanced high-temperature materials and more effective turbine blade cooling; and techniques to more efficiently recuperate energy while satisfying thermal and power requirements. This area also leverages some of the work described in the energy and environment section for reducing aircraft fuel burn.

Goal 4—Demonstrate increased power generation and thermal management capacity for aircraft (see p. 28)

Additional sensor packages and advanced electronics, along with the potential development of airborne directed energy weapons, require dramatic improvements in power and thermal management. At the same time, higher temperature propulsion systems and higher flight speeds will yield much higher heat loads to be managed by future aircraft, with some projections of heat loads reaching 10 times those of tactical military aircraft such as the F-15 or F-16. Key technologies to improve power generation and thermal management include system-level modeling and simulation; compact integrated power and thermal management systems; high-temperature, high-pressure pumps and actuators; high-temperature heat exchangers; high-temperature fuel and oil systems; and advanced material solutions to support these subsystems.

Goal 5—Demonstrate sustained, controlled, hypersonic flight (see p. 28)

Several recent efforts have successfully demonstrated cruise at hypersonic speeds, the flight regime beyond approximately Mach 5. These have included tests with air-breathing engines at speeds of Mach 5, 7, and 10. Flight durations at these speeds have been short due to fuel volume and thermal management limitations. Accelerating flight and sustained thermal balance at hypersonic speeds continue to pose significant challenges, though both are planned be demonstrated in the near term. Even with these anticipated successes, routine hypersonic flight will be extremely challenging, requiring continued R&D into

all areas of high-speed atmospheric flight, including integrated aircraft design, air vehicle and propulsion system integration, aerodynamics, aerothermodynamics, structures and materials, lightweight and durable thermal protection systems, controls, supersonic combustion, and combined-cycle propulsion concepts that operate across the subsonic to hypersonic flight regimes.

Goal 6—Develop capabilities for UAS NAS integration (see p. 28)

Military, civil, and commercial demand for the services provided by UAS continues to increase dramatically. Integration of UAS into the NAS requires the assurance of safe and efficient operation during all phases of flight. While some level of safety can be achieved through procedural means, this does not fully comply with regulatory requirements and therefore entails operational restrictions. Technical improvements to system capabilities, such as "Sense and Avoid," enable increased access to the NAS. Technical improvements in the evaluation of flight safety enable a repeatable, timely verification and validation of such capabilities.

UAS airspace integration was identified as a fundamental challenge in the 2007 National Plan for Aeronautics Research and Development and Related Infrastructure, but no goal and associated objectives were established, largely due to a lack of understanding and consensus on the issue. Since that time, significant progress has been made in understanding the fundamental R&D issues associated with UAS airspace integration in the NAS, enabling this biennial update to the National Plan to establish a goal for UAS NAS integration. It is anticipated that both military and civil demand for UAS airspace integration will continue to grow and drive increased impetus for this goal.

Research addressing airspace integration must address airworthiness, flight control, automation, command and control, and risk of collision with other aircraft. Research must also address systems that enable both UAS self-separation and collision avoidance from cooperative and non-cooperative aircraft and with and without operator input and/or air traffic control services. Research must address impacts on the safety and efficiency of the existing airspace system. Efforts in this area leverage research described in the mobility and aviation safety sections on automation systems and integration of aircraft with different performance characteristics in the NAS.

Table 2. National Security and Homeland Defense R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Demonstrate increased cruise lift-to-drag and innovative airframe structural concepts for highly efficient high-altitude flight and for mobility aircraft (see p. 25)	Develop design methods for efficient, flexible, adaptive, and lightweight aerostructures Demonstrate conformal load-bearing antenna elements and shape sensing subsystems	Demonstrate 20% delay in laminar to turbulent transition over a 30° swept laminar flow airfoil Demonstrate key component technologies for novel configurations with a substantial improvement in lift-to-drag ratios for unmanned intelligence, surveillance, and reconnaissance applications	Flight demonstrate novel aerodynamic configurations with a substantial improvement in lift-to-drag ratios for unmanned intelligence, surveillance, and reconnaissance applications
	Develop novel configurations for mobility aircraft through advanced aerodynamics and structural concepts	Demonstrate key component technologies for novel configurations with >25% improvement in lift-to-drag ratios for mobility aircraft	Demonstrate novel configurations with >25% improvement in lift-to-drag ratios for mobility aircraft
Goal 2 Develop improved lift, range, and mission capability for rotorcraft (see p. 25)	Increase power to weight (+40%) and reduce noise of main rotor gearbox (–15 dB)	Increase power to weight (+70%) and reduce noise of main rotor gearbox (–20 dB)	
	Reduce vibratory loads 20%; improve forward flight efficiency 2%	Reduce vibratory loads 25%; improve forward flight efficiency 5%	Reduce vibratory loads by 30% and improve forward flight efficiency by 10%
	Increase hover efficiency by 4%	Increase hover efficiency by 7%	Increase hover efficiency by 10%
	Develop analytical tools and component technologies for advanced low-noise concepts	Flight test tactically significant acoustic signature reduction	Demonstrate 50% reduction in acoustic perception range
Goal 3 Demonstrate reduced gas turbine specific fuel consumption (see p. 26)	Design and demonstrate high pressure compressor technologies for high overall pressure ratio propulsion systems through key component tests	Demonstrate a high-overall pressure ratio propulsion system enabling a 25% or greater specific fuel consumption reduction	Develop and demonstrate advanced propulsion concepts with variable cycle features and high overall pressure ratio enabling a greater than 30% specific fuel consumption reduction
	Design and demonstrate variable cycle propulsion component technologies through key component tests	Demonstrate a variable cycle propulsion system enabling a 25% or greater specific fuel consumption reduction	
Goal 4 Demonstrate increased power generation and thermal management capacity for aircraft (see p. 26)	Demonstrate 2× operating temperatures for power electronics	Demonstrate 5× increase in thermal transport and heat flux for power electronics	Demonstrate 10× increase in thermal transport and heat flux for directed energy weapons
	Demonstrate 4× increase in generator power density for directed energy weapons		Demonstrate 50% weight and volume reduction for aircraft power and thermal management systems
	Demonstrate >60 W/kg power density for UAS rechargeable energy storage	Demonstrate 2× power density for UAS hybrid energy storage	
Goal 5 Demonstrate sustained, controlled, hypersonic flight (see p. 26)	Demonstrate sustained, controlled flight at Mach 5–7 for a duration greater than 5 minutes using an expendable airframe and hydrocarbon fuel	Ground test scramjet propulsion systems to 10× airflow of today's scramjet technology Increase effective heat capacity of endothermically cracked hydrocarbon fuel to extend vehicle thermal balance point beyond Mach 8	Demonstrate scramjets operable to Mach 10 on hydrocarbon fuel and to Mach 14 on hydrogen fuel
	Ground test hypersonic vehicle component technologies, including high-temperature structures, thermal protection systems, adaptive guidance and control, and health management technologies	Flight test air-breathing vehicle technologies beyond Mach 7 and durations greater than 10 minutes for application to space launch systems and possible reconnaissance/strike systems Demonstrate a lightweight, durable airframe capable of global reach	Validate an optimum air vehicle solution that demonstrates an efficient thermal management approach to accommodate the combined thermal loads of the aero-thermal environment, integrated engines and internal vehicle subsystems
Goal 6 Develop capabilities for UAS NAS integration (see p. 27)	Develop a flight safety case modeling capability including data collection methods Define the appropriate target level of safety and the process for evaluation	Validate and verify flight safety assessment capability	Demonstrate rapid, routine flight safety assessments
	Demonstrate sense and avoid capability for large UAS in low traffic environments	Demonstrate sense and avoid for full range of UAS sizes and multiple UAS in low density airspace and mixed fleet interactions	Demonstrate sense and avoid for full range of UAS in all classes of airspace including high density terminals and metroplex areas

AVIATION SAFETY IS PARAMOUNT

Every individual who enters an airport or boards an aircraft expects to be safe. To that end, continual improvement of flight safety must remain at the forefront of the U.S. aeronautics agenda.

INTRODUCTION

The current air transportation system—especially for commercial aviation—is extremely safe. The task before the United States is to maintain and improve this safety record as aviation traffic increases and new forms of aircraft create an increasingly complex aviation environment. As introduced in the mobility section, the potential increase in operations by 2025 implies an increased complexity in the monitoring and control of aircraft, as well as reduced time to react to problems. This requires new technologies, operating procedures, and methods for predicting and preventing safety issues if the increased complexity of aviation operations is to be achieved safely. If safety is addressed early in the design of fundamental transformations of the NAS, even greater levels of safety can be achieved.

Likewise, there is a need to understand the safety implications of a much broader variety of aircraft operating in the NAS that will be enabled by the NextGen. In the next 10 to 15 years, expanded general aviation, rotorcraft operations, UAS, and the nascent air taxi business will all present tremendous opportunities to meet the demands of consumers, but they will also provide new and unique safety concerns. Future generations of advanced aircraft that may enter into service in the 2020–2025 time frame, market permitting, will likely use revolutionary configurations such as hybrid wing-body, small supersonic jets, cruise-efficient short take-off and landing, or advanced rotorcraft and may pose even more safety concerns. The operational characteristics of these aircraft, their safety envelopes, visibility to other aircraft, and responsiveness must be understood and considered when developing a safe air transportation system. The combined effect of increased complexity and diversity of aircraft creates major challenges to ensuring continued high levels of aviation safety while achieving the aviation capabilities needed for the nation's future.

STATE OF THE ART

The aviation industry provides by far the safest mode of transportation available in the United States. By the end of 2007, the average commercial fatal accident rate had declined to its lowest level—0.022 per 100,000 departures—a 57% drop over the last 10 years.[11] The decline in the accident rate highlights that safety is a core value throughout the entire aviation industry, across all classes of vehicles and the operation of the airspace system. The current system has reached a state where low accident levels for commercial aviation, coupled with the traditional forensic investigation approach to aviation safety, are

11 Federal Aviation Administration, "2008–2012 FAA Flight Plan: Charting the Path for the Next Generation," 2007, p. 15, http://www.faa.gov/about/plans_reports/media/FPP_Flight%20Plan%202008-2012.pdf.

yielding fewer insights capable of significantly improving aviation safety. Advances in prognostic techniques enable insights into system safety through examination of large numbers of normal operations, as well as incident events.

Despite the outstanding safety record for modern aviation, accidents still occur and safety concerns remain, including issues such as aircraft aging, sensing of vehicle health, and icing. Congestion is an ongoing concern in the air and on the ground in several areas of the country. Without intervention, congestion and its related safety risks can be expected to increase with future increases to capacity. In addition, the fabrication methods and capabilities of new aircraft are also changing, and the safety performance of such changes needs to be understood. Future aircraft will be made from advanced, novel materials, in more complex configurations, with more technically advanced subsystems and avionics. When accidents do occur, it is imperative that the probability of survival for the passengers and crew on board be as high as possible.

It is anticipated that automation will play a key role in future aircraft and the future NAS as enabled by NextGen. The proper application of automated capabilities, ranging from intelligent displays, to decision aids and other interactive systems, to fully autonomous systems, will require advances in human-machine integration capabilities, better decision-making through data and knowledge mining systems, and control systems that adapt to future changes in the aircraft configuration (including UAS) and changing environmental conditions. In addition, improved systems and software assurance practices will be essential to the implementation of automation technologies. Software was identified as critical to aviation by both the President's Council of Advisors on Science and Technology ("the percentage of aircraft functionality enabled by software has grown from 10% in the 1960s to over 80% today"[12]) and the National Academy of Sciences ("Dependable software will be a linchpin of safe air transport in the coming decades"[13]).

Collectively, these developments are leading to greater system complexity, including airspace systems comprising tightly coupled air and ground functions relying on automation, and including aircraft systems that distribute and integrate many functions across an increasing number of aircraft components, resulting in a dramatic increase in on-board flight-critical software. Current methods of ensuring that a design meets desired safety levels (including methods for verification and validation) will likely not scale to these levels of complexity nor be able to coordinate the often disparate considerations of software, digital systems, human performance, and operational factors. Additionally, systems assurance practices, particularly requirements validation, have been identified as critical

12 President's Council of Advisors on Science and Technology, "Leadership Under Challenge: Information Technology R&D in a Competitive World," August 2007.

13 "Software for Dependable Systems: Sufficient Evidence?" D. Jackson, M. Thomas, and L. I. Millett, Eds., National Research Council of the National Academies, May 2007.

to safe system implementation. Thus, because of the added complexity introduced by increased automation, existing safety assurance processes and practices may prove to be prohibitive, in terms of cost and time, when applied to the introduction of future innovative operations and technologies.

FUNDAMENTAL SAFETY CHALLENGES TO OVERCOME

Shortfalls associated with the state of the art discussed above will have to be overcome to continually improve safety in the decades ahead. The following are the major challenges:

- Predicting, monitoring, and assessing the health of aircraft, at the material, subsystem, and component level, more efficiently and effectively.
- Rapidly but safely incorporating technological advances in avionics, software, automation, and aircraft and airspace concepts of operation and operating procedures, by assuring their safety through a rigorous verification and validation process in a cost- and time-effective manner.
- Applying novel sensing, automatic and manual control, and estimation techniques to assist in stabilizing and maneuvering next-generation aircraft in response to safety issues ranging from multiple-aircraft conflicts, to on-board system failures, to unintended entry into unusual flight conditions and environmental hazards.
- Understanding and predicting system-wide safety concerns of the airspace system and the vehicles as envisioned by NextGen, including the emergent effects of increased use of automation to enhance system efficiency and performance beyond current, human-based systems, through health monitoring of system-wide functions that are integrated across distributed ground, air, and space systems.
- Understanding the key parameters of human performance in aviation to support the human contribution to safety during air and ground operations for appropriate situational awareness and effective human-automation interaction, including during off-nominal and degraded situations.
- Ensuring safe operations for the complex mix of vehicles (including UAS) anticipated within the airspace system enabled by NextGen.
- Enhancing the probability that passengers and crew will survive and escape safely when accidents do occur.

AVIATION SAFETY R&D GOALS AND OBJECTIVES

To continue today's impressive safety record while increasing the density of air traffic and the diversity of platforms will require foundational research and advanced system development in three focus areas: reliable and robust aircraft, safe air and ground operations, and accident survivability. The three goals and associated objectives listed below address the major challenges in continually improving safety in the NextGen.

Goal 1—Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems (see p. 36)

Aircraft-level health-management systems, including sensors and analytical tools, will be developed that can identify problems before accidents occur. Research in health management requires not only monitoring and detecting, but also confident prognostics of latent potential failures before they occur. While health management is informed by the known accident and incident records of other vehicles, it is not restricted to those known conditions. The development of health management systems requires a deeper understanding of aging and degradation mechanisms in airframe and aircraft systems.

To reduce accidents caused by loss of stability and an aircraft's inability to maneuver, research will be performed that will facilitate implementation of advanced systems logic and architectures for avoiding, detecting, and resolving conditions that can lead to such accidents. Loss of stability and maneuverability can result from an upset condition due to adverse conditions such as actuator failures, structural damage, or stall-departure resulting from, for example, inadvertent encounters with hazardous weather conditions such as convective weather or icing. Recent incidents have highlighted new potential contributors to such upset conditions, including high ice water content atmospheric conditions capable of causing ice accretion on vital aircraft sensors and inside jet engines, at temperatures colder and altitudes higher than icing was hitherto known to occur.[14]

Advanced health-management systems and advanced aircraft control techniques will require extensive research in the verification and validation of complex and potentially adaptive, flight-critical systems in the aircraft and as part of the airspace systems. This will include research into coordinated safety assurance methods examining in operational contexts the combined safety properties of distributed, integrated adaptive systems; software; automation; and human performance, which are also noted in the next goal. Of particular importance is the need for such methods to be cost- and time-effective, and for these safety assurance methods to have applicability to innovative and novel technologies for which established methods do not exist.[15]

Research will also be needed for the development of improved aircraft systems and structures, physics-based prediction of material properties, and designs and maintenance technologies to reduce material and structural failures during operational use. Research to incorporate maintainability and human operability early into the design process at both the subsystem and system level is also important.

14 J. Mason, W. Strapp, and P. Chow, "Ice Particle Threat to Engines in Flight," AIAA 2006-0206.

15 Ibid.

Goal 2—Develop technologies, for manned and unmanned systems, to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air (see p. 36)

Focused research on NextGen airspace system safety is directed at understanding the impact of operational concepts and organizational structures within the NextGen on safety, including establishing robustness to off-nominal conditions as a design goal. New safety assurance methods and tools will be developed to analyze airspace for safety concerns such as system-wide emergent behaviors that may arise even when all system components and human operators perform as expected. Likewise, understanding airport and airspace designs that can reduce the likelihood of incidents on the ground and in the air is important. These objectives will consider not only technological developments, but also the design of operating procedures and the extent human performance in nominal and off-nominal or degraded situations is impacted by automated systems and decision aids, complementing the increased airspace performance gains through effective human-automation interaction described in the mobility section.

Research will address the challenges introduced by greater density and diversity of flight operations. To allow more aircraft to operate in the airspace, aircraft users and developers will require improved understanding of aircraft interaction dynamics; improved aircraft interfaces, including automation systems; and system adaptability to changing conditions. It is critical to develop improved human-machine interfaces while safely increasing flight deck[16] and ground controller automation. Of particular note, research will be conducted to improve the ability of humans and automated systems to collectively detect and help aircraft avoid hazardous weather.[17]

An increased number of aircraft in the air transportation system not only increases the aircraft density in the air, but also on the ground. To address this increased demand, research is needed to develop systems that improve pilot and controller awareness of airport surface conditions (aircraft locations, ground vehicle locations, runway occupancy, and pavement conditions), particularly in low-visibility situations. While improving the situational awareness of flight crews and ground controllers is critical to reducing incidents and accidents on the ground, understanding changes to airport designs that can reduce the likelihood of incidents on the ground is also important. Results of research under this goal will be directed at developing technologies for new ground capabilities to be integrated into aircraft, control towers, taxiways and runways.

Accidents will also be reduced by identifying system-wide safety risks through research on prognostic methodologies capable of organizing, managing, and mining data from all

16 These interfaces include not only the flight deck for crewed vehicles, but also the UAS operator for unmanned vehicles, in order to support the research requirements discussed not only here, but in the mobility and national security and homeland defense sections as well.

17 Weather data as described in mobility section R&D Goal 3, "Reduce the adverse impacts of weather on air traffic management decisions."

users in the entire airspace system. These prognostic methodologies will be able to actively identify safety risks to the affected users by integrating both objective statistical techniques and operator reports of safety concerns.

In the NextGen system, many system functions, such as separation management, trajectory management and flow management, are contingent on the integrity and integration of data and information across many distributed air and ground systems. Moreover, those systems functions will be variable (e.g., variable separation standards) and based on the health and level of performance of the participating systems (e.g., the accuracy, integrity, and update rate of surveillance information from aircraft). Therefore, research is required to address the health of critical airspace system functions, to ensure that information integrity is properly factored into assessments made from the information, and to develop techniques for real-time monitoring and assessment.

NextGen operations, and the combination of subsystems (ground and aircraft) that will correspond to them, represent a system of greater complexity than ever developed in any domain, even as they also must achieve the highest levels of safety. This requires understanding failures and degradations in such a complex system, especially when created by, or exacerbated by, the integration of functions that are distributed across ground, air, and space elements. To support the implementation of such a system, techniques must be developed to enable a priori safety assurance of critical system functions and ultimately to provide methods for cost- and time-effective verification and validation of flight-critical systems, as also discussed in the mobility section.

Until a few years ago, UAS were primarily used by the DOD. However, interest in using UAS has escalated rapidly, and now there is broad interest across a wide range of Federal and non-Federal entities. Because of escalating interest and activity, UAS access to the NAS has become a priority. To ensure the safe flight operations of UAS, procedures for certification, licensing, training, inspection, maintenance, and operation of UAS are needed to ensure their integration into the NAS without causing delays, reducing capacity, or compromising safety in the air as well as on the surface. It is anticipated that flight operations will extend from remote and sparsely populated areas, to major metropolitan areas where air traffic and population are dense. Thus, it is essential that UAS and the complex flight-critical systems needed for safe unmanned operations be predictable and reliable. Aviation safety UAS R&D efforts are intended to cover a broad range of activities and be consistent with activities in the mobility and national defense and homeland security sections.

Goal 3—Demonstrate enhanced passenger and crew survivability in the event of an accident (see p. 36)

Enhancing and protecting the safety of passengers, crews, and ground personnel in the event of an accident is the third research challenge to improving aviation safety. The research can be broken into two categories: (1) improving crash survivability of aircraft structures and (2) improving evacuation and accident response procedures. At present, nearly half the aircraft fatalities in impact-survivable accidents are due to the effects of smoke and fire. Research into understanding and reducing flammability of aircraft interiors is essential to making impact accidents survivable for crews and passengers, as well as firefighters. Additional research to increase the understanding of the effect(s) of alternative fuels on propulsion system fire safety, post-crash cabin fire safety and occupant survivability, and the smoke toxicity of advanced aircraft materials will be needed.[18] Restraint systems integrated into and as strong as the supporting aircraft structure offer the possibility of providing increased occupant survivability; research into these systems is essential. Finally, research on current and future evacuation and accident response procedures will ensure that new aircraft entering the airspace system are as safe as—if not safer than—today's aircraft.

18 Alternative fuels as described in the energy and environment section R&D Goal 1, "Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability."

Table 3. Aviation Safety R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems (see p. 32)	Develop vehicle health-management systems to determine the state of degradation for aircraft subsystems	Develop and demonstrate tools and techniques to predict, detect, and mitigate in-flight damage, degradation, and failures	Develop reconfigurable health-management systems for managing suspect regions in N+2 vehicles
	Develop and test adaptive-control techniques in flight to enable safe flight by stabilizing and establishing maneuverability of an aircraft from an upset condition	Develop, assess, and validate methods to avoid, detect, and recover from upset conditions	Develop formal methods to verify and validate the safety performance margins associated with innovative control strategies, decision-making under uncertainty, and flight path planning and prediction
	Develop improved mitigation techniques that prevent, contain, or manage degradation associated with aging, and show that tools and methods can predict the performance improvement of these techniques	Deliver validated tools and methods that will enable a designer or operator to extend the life of structures made of advanced materials	Develop advanced life-extension concepts (designer materials and structural concepts) by using physics-based computational tools
Goal 2 Develop technologies to reduce accidents and incidents through enhanced aerospace vehicle operations on the ground and in the air (see p. 33)	Validate and verify methods that enable improvements in pilot and controller workload, awareness, and error prevention and recovery, including during off-nominal scenarios, given the increased automation assumed in NextGen	Develop human-machine interfaces that enable effective human performance during highly dynamic conditions and allow for flexible intervention to ensure safety	Develop formal methods to verify and validate the safety of complex airspace operations
	Develop flight deck displays and automation to convey up-to-date weather conditions and near-term forecasts Investigate in-situ and remote observing systems, technologies, and architectures that will provide hazardous and other weather information	Develop an integrated flight deck system that alerts flight crews of all on-board and environmental hazards and defines and coordinates an appropriate, safe flight path Develop in-situ and remote observing technologies, systems, and architectures that will provide weather information to flight crews and air traffic controllers	Develop high-confidence, flight deck decision-support tools that use single authoritative information source for shared decision-making between air traffic management and flight crew about weather and other concerns in planning a safe flight path
	Develop advanced tools that translate numeric (continuous and discrete) system performance data into usable, meaningful information for prognostic identification of safety risks for system operators and designers Understand the concepts of degradation and failure as well as other potential safety issues associated with critical system functions integrated across highly distributed ground, air, and space systems (including UAS)	Develop advanced methods to automatically analyze textual safety reports and extract system performance information for prognostic identification of safety risks for system operators and designers Develop techniques to enable a priori safety assurance and real-time monitoring and assessment of critical system functions across distributed air and ground systems (including UAS)	Develop fundamentally new data-mining algorithms to support automated data analysis tools to integrate information from a diverse array of data resources (numeric and textual) to enable rapid prognostic identification of system-wide safety risks Validate and verify the safety of complex flight-critical systems (including UAS) in a cost- and time-effective manner
Goal 3 Demonstrate enhanced passenger and crew survivability in the event of an accident (see p. 35)	Develop occupant-restraint design tools that support occupant crash protection that is as strong as the fixed- and rotary-wing aircraft structure	Validate integrated vehicle structure and occupant restraint tools	Validate integrated vehicle structure and occupant restraint tools for advanced concept vehicles
	Develop analytical methodologies to model dynamic events in aircraft crashes to enable the development of lightweight and crash-absorbing airframe technologies for the fixed- and rotary-wing legacy fleet	Establish analytical methodologies to model dynamic events in aircraft crashes to enable the development of lightweight and crash-absorbing airframe technologies for advanced aircraft, including those made with advanced composite and metallic materials	Validate and verify analytical methods that model dynamic events in aircraft crashes for airframe structures
	Assess and reduce flammability and smoke toxicity of advanced materials to be used in aircraft platforms	Determine fuel vapor characteristics of alternative aviation fuel spills for post-crash survivability	Validate and verify methodologies to determine impact of alternative fuels on cabin material flammability and propulsion system fire safety and survivability

ASSURING ENERGY AVAILABILITY AND EFFICIENCY IS CENTRAL TO THE GROWTH OF THE AERONAUTICS ENTERPRISE, AND THE ENVIRONMENT MUST BE PROTECTED WHILE SUSTAINING GROWTH IN AIR TRANSPORTATION

Aviation must have reliable sources of energy and use that energy efficiently to enable aircraft and an air transportation system to meet growing demand in an economic fashion. Appropriate environmental protection measures must be part of strategies for continued growth in air transportation.

INTRODUCTION

Commercial aviation and military aviation have transformed the United States and the world during the last 50 years, but there are concerns about the energy efficiency and environmental impact of the aviation enterprise and the future availability, supply security, and cost of aviation fuels. Addressing these issues is becoming more compelling. A number of domestic and international climate-related policy actions under consideration (e.g., cap and trade schemes, CO_2 standards) may profoundly impact the aviation industry. Effectively improving the energy efficiency of the aviation enterprise would ease the demand for petroleum and reduce cost. It could also have a positive impact on the environment by reducing greenhouse gas emissions and air quality impacts. Concerns about aviation's impact on the environment have grown as aviation has grown. Unless effectively addressed, environmental concerns could increasingly restrict the ability of the aviation system to grow to meet national economic and mobility needs. Airport expansion or new construction is often a contentious issue because of noise, air quality, and water quality concerns. Although aviation currently contributes only 2%–5% of anthropogenic greenhouse gases impacts,[19] emissions from the sector are expected to grow in absolute terms without effective mitigating actions.

STATE OF THE ART

Nearly 100% of the fuel used in aviation operations today is derived from petroleum, although progress is being made toward adoption of alternative fuels. The commercial supply of energy and its price stability remain critical business concerns; fuel currently represents the largest operating cost for U.S. airlines. Every one-cent increase in fuel price translates into an additional $190 million in annual costs for the commercial aviation industry.[20] Advanced engines have improved performance and modern large commercial aircraft turbine engines are designed to optimize fuel efficiency, with overall engine efficiency around 30% for high-bypass turbofans.

19 Intergovernmental Panel on Climate Change Fourth Assessment Report, "Working Group 1: The Physical Science Basis," 2007; D. S. Lee, D. W. Fahey, P. M. Forster, P. J. Newton, R. C. N. Wit, L. L. Lim, B. Owen, and R. Sausen, "Aviation and Global Climate Change in the 21st Century," *Atmos. Environ*. 43 (2009): 3520–3537.

20 Air Transport Association, http://www.airlines.org/economics/energy/.

Noise issues include takeoff, landing, taxi and engine run-up; aircraft flying over very quiet areas such as national parks; and sonic booms associated with supersonic flight. Aviation noise is primarily a quality-of-life issue for the public, although there are also associated health impacts. Despite growing emphasis on climate and air quality issues, noise remains the key environmental concern that undermines efforts to increase airport capacity. Aircraft noise reduction has been historically driven by the introduction of new technologies. Further technology gains resulting in noise reduction will be challenging, but both the Quiet Aircraft Technology program, sponsored by NASA and the FAA, and the Silent Aircraft Initiative, led by the Massachusetts Institute of Technology and Cambridge University, have laid the technological foundation for further gains.

Emissions of nitrogen oxides (NO_x), carbon monoxide, unburned hydrocarbons (HC), some of which are classified as hazardous air pollutants), and particulate matter (PM) are of health concern in the vicinity of airports. Some studies[21] that have quantified health risk exposure due to aircraft related PM suggest a reduction in direct emissions of black carbon and gaseous precursors (NO_x, sulfur oxides or SO_x and HC) of volatile PM to mitigate their associated health risk exposure. Emissions of CO_2, water vapor, NO_x, SO_x, and PM in the upper troposphere and stratosphere are also of concern because of their direct and indirect effects on Earth's climate. There is a good understanding regarding the fundamental physics and chemistry of the effect of aircraft-generated CO_2 on climate, but large uncertainties remain in our present understanding of the magnitude of climate impacts due to aviation NO_x emissions, contrails, and contrail-induced cirrus clouds. The impact of particulates and their role in enhancing cirrus cloudiness—and subsequently climate change—remain poorly understood.

FUNDAMENTAL ENERGY AND ENVIRONMENTAL CHALLENGES TO OVERCOME

In order for the aviation sector to be able to continue to evolve and grow, concerns about environmental impacts and energy efficiency must be addressed, as evidenced by the strong environmental opposition to the redesign of airspace in some major metropolitan areas. Aviation must also have a reliable, diverse, and cost-effective energy supply. Key energy and environment challenges for aviation include the following:

- Development of alternative aviation fuels, including renewable options, and energy is critical to enabling energy sources that are more diverse and environmentally friendly than those currently derived from petroleum.
- A more complete understanding of the complex interdependencies that exist between aircraft noise, emissions, and fuel burn is required for tackling these issues in a cost-beneficial manner.

21 "High-Priority Compounds Associated with Aircraft Emissions," http://web.mit.edu/aeroastro/partner/reports/proj11/p11compndsemiss.pdf, and "Aircraft Impacts on Local and Regional Air Quality in the United States," http://web.mit.edu/aeroastro/partner/reports/proj15/proj15finalreport.pdf.

- Improvement is required in the capability to optimize aircraft noise, fuel efficiency, and emissions reductions using advanced technologies, operational procedures, and computational models.
- Scientific uncertainties must be reduced to better inform appropriate action. Such uncertainties include the overall life-cycle impacts of alternative aviation fuels; the impact on climate of direct aviation emissions, such as NO_x and PM, as well as from contribution of contrails that lead to cirrus cloud formation; and the impact of PM and hazardous air pollutants from aviation emissions on air quality. Key process uncertainties to be overcome include approaches for quantifying aviation emissions and their global distribution. This quantification is also critical for assessing impacts to human health.
- Improvement in the modeling of pollutant concentrations around airports and throughout the atmosphere is needed. The scientific community has made some progress in quantifying the scale of, and the metrics associated with, aviation's impact on climate, including the relationships between long-term impacts like CO_2 and shorter lived impacts like NO_x emissions, contrails, and cirrus clouds. However, there is currently not full consensus on these approaches.

ENERGY AND ENVIRONMENT R&D GOALS AND OBJECTIVES

The United States must lead in effectively tackling aviation's energy and environmental issues so that the flying public can continue to enjoy the benefits of mobility and so that aviation activities do not diminish the quality of life for residents living near airports, adversely affect human health, or contribute to longer term impacts such as climate change. In order to maximize these benefits, U.S. environmental policy and future technological capabilities will need to be aligned. Meeting these goals and objectives will help lead to improved energy security (e.g., supply diversity and enhanced energy efficiency); reduction of impacts on public health due to noise, emissions, and compromised water quality; and a reduction in the impact of aviation emissions on global climate.

Achieving these goals requires a significant advance in the state of the art in terms of technology and current aviation capabilities. Crucial to this advancement is the pursuit of long-term, stable foundational research, including atmospheric and combustion chemistry, fluid mechanics of internal flows, acoustics, and computational science. For purposes of the energy and environment R&D goals and objectives, "enable" means to advance the development of technologies or systems to levels that appropriately facilitate eventual industry uptake for commercial applications; implementation will add to the time line for reducing environmental impacts and achieving energy security.

Goal 1—Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability (see p. 43)

Exploring the suitability of alternative sources of energy for aviation, particularly those produced from renewable resources, is essential to the aviation industry. Aviation requires

energy-dense fuels now and into the foreseeable future. For economic security reasons, fuel needs to be produced from diverse resources. A clean-burning, sustainable renewable fuel that contains few aromatic components and sulfur, operates at high temperature, and produces little particulate emissions is desired. The most reasonable near-term choice is the use of indigenously available feedstocks, such as natural gas, coal, oil shale, and petroleum coke, to produce drop-in replacements/supplements for petroleum-derived jet fuels. Renewable biofuels are currently not capable of supplying a large percentage of fuel needs, but higher yielding future feedstocks, such as algae or cellulosic biomass, may improve feedstock supply. The main advantage of using biofuels may be their potential to reduce overall life-cycle CO_2 impact. If the performance and cost issues can be overcome, biofuels are envisioned to be blended with synthetic or conventional jet fuels. Biomass offers the attraction of potentially lower net CO_2 emissions in the mid term. Other renewable fuels are attractive longer term options. Research will identify and assess potential environmental and performance costs and benefits of alternative fuels, with particular focus on limiting the environmental footprint of aviation.

In the near term, research will be focused on evaluating the performance of alternative fuels in comparison with conventional fuels in associated systems and addressing the technical issues involved in their certification. Evaluating the environmental impacts of the production of alternative fuels and improving their viability are also important.

In the mid term, the research will focus on enabling affordable renewable "drop-in" fuels that have large production potential, meet health and safety requirements, and are certifiable.[22] Renewable aviation fuels that reduce carbon footprints are key to limiting growth in aerospace emissions. Mid term research will also enable development of environmental best practices to help guide the production of all jet fuels.

In the far term, renewable, fully biomass-derived aviation fuels meeting the same performance and operation criteria as those for drop-in fuels will be enabled. These renewable fuels may require some aircraft and engine changes, as well as new fuel supply systems and airport infrastructure for successful adoption, possibly due to use of some materials such as seals, which were not designed for fully alternative fuels, in the legacy systems.

Goal 2—Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system (see p. 43)

In 2004, the U.S. commercial aviation industry moved 12% more people and 22% more freight than it did in 2000, while burning 5% less aircraft fuel.[23] Even so, fuel is one of the

22 A drop-in fuel is a fuel that can be used in existing aircraft and supporting infrastructure; drop-in fuel properties may vary from the average properties of conventional fuels within existing specification limits.

23 I. Waitz, J. Townsend, J. Cutcher-Gershenfeld, E. Greizter, and J. Kerrebrock, "Report to the U.S. Congress, Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions," December 2004.

most significant costs to civil and military aviation. Fuel efficiency is not only good for the environment and energy security, it also makes business sense. Enabling new technologies, procedures, and improvements to aircraft and air traffic management to reduce fuel burn of aviation is crucial. The approaches to reduce vehicle fuel consumption are to increase the vehicle cruise lift-to-drag ratio, decrease the empty weight fraction, and increase overall engine efficiency.

Key to reducing drag is the ability to accurately represent and predict the airflow over the aircraft. This capability will be accomplished through the development of physics-based methods, validated by high-quality experimental or flight data. The new methods will enable developing technologies leading to a reduction in drag sources, such as turbulence and separation, and an increase in lift (with further reduced drag) by enhancing laminar flow. Active-control methods that prolong laminar flow, delay separation, or increase circulation will also be developed. Propulsive efficiency can be improved by advancing analytical methods to enable active flow control over fan and turbine blades, similar to that for the airframe. Other approaches such as enabling an ultra-high bypass engine will also be pursued.

Advances in material and structures technology will reduce the overall structural weight of the airframe. These advances include inherently stronger, lighter weight materials, as well as more efficient structural concepts. Research in airframe and propulsion efficiency also leverages the work described in the national security and homeland defense section for improving aircraft lift-to-drag ratios and for reducing propulsion system specific fuel consumption. In addition to subsonic flight efficiency, both airframe and propulsion efficiencies are needed to achieve the cruise efficiency required for supersonic flight. Fuel efficiency goals for supersonic air vehicles are directly addressed in the mobility section and increased fuel efficiency is a key enabler for practical, sustained supersonic flight. In the near term, new materials and advances in structural systems will enable a weight reduction for high-temperature airframe and propulsion systems for supersonic aircraft. Advances in communication, navigation, and surveillance technology can be leveraged to optimize aircraft arrival and departure procedures, along with sequencing and timing on the surface, in the terminal area, and en route, thereby increasing airport and airspace throughput and reducing fuel burn.

Analytical tools to evaluate the elements associated with vehicle fuel consumption and fuel efficiency and to analyze the effect of technology solutions are critical to determining the value of various technology or operational approaches. In the near term, research will enable metrics and first-order empirical analytical capabilities to evaluate fuel efficiency enhancement strategies. In the mid term, the focus will be on maturing existing analytical tools that generally rely on empirical correlations and first-order approximations to include the introduction of additional elements, bringing the methods closer to a physics-based

representation. The far-term objective will be the transition from the mid-term advanced empirical analytical tools to physics-based tools that rely on foundational principles. These analytical capabilities will require high-quality experimental or flight data for validation. Note that the specific objectives of Goal 2 are closely coupled with Goal 3, because decreasing fuel burn decreases the environmental impact of the aviation system.

Goal 3—Advance development of technologies and operational procedures to decrease the significant environmental impacts of the aviation system (see p. 44)

To ensure that technology and operational goals are appropriate, research on the environmental impacts of aviation is needed. It is necessary to focus on sufficiently reducing the uncertainties regarding the impacts of aviation on the environment so that potential cost-beneficial solutions that minimize environmental impacts can be explored. Research should assess the relationships among the public health, climate, and environmental impacts of aircraft emissions. Some of these aviation effects include emissions in the stratosphere, troposphere, and near the ground; contrails and contrail-induced cirrus cloud formation; ozone depletion associated with supersonic flight; and the emissions effects of fuel components such as sulfur. Water quality impacts of airport operations are also a concern. In the mid term, the focus is on furthering scientific understanding to enable understanding the interrelationships of various emissions (e.g., relative benefits of focusing on reducing NO_x versus CO_2). Hence, in the mid term, mitigation strategies focus on limiting emissions while avoiding strategies that may worsen impacts. In the far term, enhanced scientific understanding will enable optimizing mitigation strategies to actually reduce the most serious impacts in the most cost-beneficial manner.

Another element of aviation's impact on the environment is noise. To address this issue, research will pursue overall reductions in noise and examine the trades between noise and emissions improvements. Efforts on source noise physics will bring together various prediction and calculation methods to characterize and reduce noise from subsonic and supersonic aircraft and rotorcraft. In addition, efforts to better understand the trades between noise and emissions on all types of aircraft (rotorcraft, subsonic, and supersonic) are aimed at (1) enabling future generations of aircraft (N+1, N+2, and N+3) that permit better management of the energy resources and environmental impact and (2) informing national and international regulatory processes for better decision-making on noise, emissions, and sonic boom issues.

The interplay between noise and emissions must be better understood to inform regional or local regulatory requirements, including regulations regarding supersonic aircraft. The objective is to cost effectively limit or reduce potential environmental health and welfare impacts of aircraft noise and emissions, while eliminating uncertainties that could lead to

misdirected or poorly targeted regulations. Enabling new technologies, procedures, and improvements to aircraft and air traffic management to reduce the noise and local and global emissions of the aviation sector is also crucial. Solutions that minimize the trade-offs between various environmental factors and result in simultaneous reductions in noise and local and global emissions are most attractive.

A new emerging issue is the correlation between landing-and-takeoff (LTO) cycle and cruise NO_x and the impact of emissions resulting from entire flight cycle on surface air quality. For some evolving engine architectures a reduction in LTO NO_x (~10% of total NO_x emitted during flight) may not be reflected at cruise (~90% of NO_x emitted during flight). This is a potentially significant design trade that must be explored more in depth.

Finally, research efforts should consider complete life-cycle issues for aircraft to facilitate environmentally friendly manufacturing processes, reuse and recycling of materials, and development of quantitative tools for environmental cost-benefit assessments particular to aviation.

Table 4. Energy and Environment R&D Goals and Objectives

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 1 Enable new aviation fuels derived from diverse and domestic resources to improve fuel supply security and price stability (see p. 39)	Evaluate performance of alternative versus conventional fuels in associated systems, including consideration of certification processes	Enable affordable "drop in"[a] fuels that have large production potential, meet safety requirements, and are certifiable Explore renewable aviation fuels that reduce carbon footprints	Enable renewable aviation fuels that meet safety requirements, are certifiable, have a large production potential, and are sustainable for aircraft and support systems
	Evaluate alternative fuel-production impacts on the environment	Enable environmental best practices in alternative and conventional fuel production	Enable technologies to ensure that new aircraft, fuel supply systems, and airport infrastructure are built to standards that allow the most environmentally beneficial alternative fuels
Goal 2 Advance development of technologies and operations to enable significant increases in the energy efficiency of the aviation system (see p. 40)	Define achievable energy efficiency gains via operational procedure improvements Research operational procedures to enhance fuel efficiency Enable fuel efficient N+1 aircraft and engines (33% reduction in fuel burn compared to a B737/CFM56)[g]	Research and enable new energy efficient operational procedures optimized for energy intensity (3–5% energy intensity improvement[b] for the energy efficient procedures over existing 2006 baseline procedures) Enable fuel efficient N+2 aircraft and engines (at least 40% reduction in fuel burn compared to a B777/GE90)[h]	Enable new energy efficient operational procedures optimized for energy intensity (6–10% energy intensity improvement for the energy efficient procedures over existing 2006 baseline procedures) Enable fuel efficient N+3 aircraft and engines to reduce fuel burn by up to 70% compared with a B737/CFM56[g] (70% is a 25-year stretch goal and assumes significant advances in novel configurations, engine performance, propulsion/airframe integration, and materials)
	Enable metrics and first-order empirical analytical capabilities to evaluate fuel efficiency enhancement strategies	Develop advanced empirical analytical capability to assess and enhance fuel efficiency enhancement strategies	Enable physics-based simulation analytical capability to optimize fuel efficiency enhancement strategies

Goal	Near Term (<5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Goal 3 Advance development of technologies and operational procedures to decrease the significant environmental impacts of the aviation system (see p. 42)	Research and develop ground, terminal, and en-route procedures to reduce noise and emissions and determine sources of significant impact	Develop and demonstrate advanced ground, terminal, and en-route procedures to reduce significant noise and emissions impacts	Develop new approaches and models for optimizing ground and air operational procedures
	Develop improved tools and metrics to quantify and characterize aviation's environmental impact, uncertainties, and the trade-offs and interdependencies among various impacts Enable quieter and cleaner N+1 aircraft and engines (32 dB cumulative below Stage 4);[c] LTO[d] NO_x emissions reduction (70% below CAEP[e] 2 standard) Continue research to identify alternatives to lead as an octane-enhancing additive in aviation gasoline	Reduce uncertainties in understanding aviation climate impacts to levels that enable limiting significant impacts Characterize $PM_{2.5}$[f] and hazardous air pollutant emissions and establish long-term goals for reducing to appropriate levels Research the technical challenges associated with achieving low NO_x and very low CO_2 and soot emissions Enable N+2 aircraft and engines; (42 dB cum below Stage 4); LTO NO_x emissions reduction (80% below CAEP 2) Enable a 70% reduction in high-altitude emissions for supersonic aircraft (reference HSR configuration)	Continue to reduce uncertainties in understanding aviation climate change impacts to levels that enable reducing significant impacts Enable physics-based analytical capabilities to characterize environmental impacts of aviation noise and emissions Enable N+3 aircraft and engines to decrease the environmental impact of aircraft (62 dB cumulative below Stage 4 (a 25-year goal); LTO NO_x emissions reduction better than 80% below CAEP 2) Enable an order-of-magnitude reduction in high-altitude emissions for supersonic aircraft (reference HSR configuration)
	Determine significant water quality impacts of increased aircraft operations	Enable anti-icing and deicing fluids and handling procedures to reduce water quality impacts determined to be significant	Enable environmentally improved aircraft materials and handling of fuel and de-icing fluids
	Develop predictive capabilities for rotorcraft noise	Enable low-noise acoustic concepts for low-noise rotary-wing vehicles	Enable low-noise operation and high-speed, fuel efficient rotorcraft
		Enable ~15 EPNdB[j] of jet noise reduction relative to unsuppressed jet for supersonic aircraft	Enable ~20 EPNdB of jet noise reduction relative to unsuppressed supersonic aircraft exhaust
	Enable reducing loudness ~25 PLdB[i] relative to military aircraft sonic booms	Enable reducing loudness ~30 PLdB relative to military aircraft sonic booms	Enable reduction of loudness ~35 PLdB relative to military aircraft sonic booms

Notes:

a A drop in fuel is a fuel that can be used in existing aircraft and supporting infrastructure; drop in fuel properties may vary from average properties of conventional fuels within existing specification limits.

b Energy intensity is the ratio of energy consumption and economic and physical output. Potential metrics for aviation could be fuel consumption per distance, per passenger distance, or per payload.

c Current noise standard for subsonic jet airplanes and subsonic transport category large airplanes, http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgFinalRule.nsf.

d LTO is the landing-and-takeoff cycle.

e CAEP is the International Civil Aviation Organization Committee on Aviation Environmental Protection.

f Particles less than 2.5 µm in diameter.

g The reference aircraft is a B737-800 with CFM56/7B engines, representative of 1998 entry into service technology.

h The reference aircraft is a B777-200 with GE90 engines, representative of 1997.

i PLdB = Perceived loudness in decibels.

j EPNdB = Effective perceived noise (level) in decibels.

FUTURE IMPLEMENTATION

Consistent with Executive Order 13419, "National Aeronautics Research and Development," and the "National Aeronautics Research and Development Policy," the R&D Plan and its companion document, the "National Aeronautics RDT&E Infrastructure Plan," will each be scheduled for update on a biennial basis in alternating years. Hence, this biennial update to the R&D Plan will be updated again commencing in 2011. Between biennial updates to the R&D Plan, it is envisioned that an R&D progress report and an analysis of areas of concern will be performed to help inform the development of the next R&D Plan. The first National Aeronautics RDT&E Infrastructure Plan is expected by the end of 2010, and its initial update is anticipated to be completed in 2012 and biennially thereafter.

ACRONYMS

ACCRI	Aviation Climate Change Research Initiative
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAEP	International Civil Aviation Organization Committee on Aviation Environmental Protection
CLEEN	Continuous Low Emissions, Energy and Noise (program)
CO_2	Carbon dioxide
DOD	Department of Defense
EO	Executive order
EPA	Environmental Protection Agency
EPNdB	Effective perceived noise (level) in decibels
ERA	Environmentally Responsible Aviation
FAA	Federal Aviation Administration
HC	Hydrocarbons
HSR	High Speed Research (program)
JPDO	Joint Planning and Development Office
LTO	Landing-and-takeoff
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System (formerly referred to as NGATS)
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen oxides
PLdB	Perceived loudness in decibels
PM	Particulate matter
R&D	Research and development
RDT&E	Research, development, test and evaluation
SO_x	Sulfur oxides
TAF	Terminal Area Forecast
UAS	Unmanned aircraft systems
UHC	Unburned hydrocarbons

Plan prepared by

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